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Anomalous Meissner Effect in Superconducting Junction with Spin-Active Interface

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Abstract

We investigate Meissner effect in normal metal/superconductor junctions where the interface is spin-active. We find that the orbital magnetic susceptibility of the normal metal depends on the temperature in an oscillatory fashion, accompanied by its sign change. Correspondingly, magnetic field and current density can spatially oscillate in the normal metal. These results stem from the generation of odd-frequency pairing due to the spin-active interface.

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Interface phenomena related to the superconductivity constitute a rich field of condensed matter physics. When a superconductor is attached to a normal metal, Cooper pairs penetrate into the normal metal which acquires superconducting correlation. This is called the proximity effect. As a result, for example, the normal metal has a gap in the density of states or shows Meissner effect[1, 2, 3]. In most cases, as lowering temperature, the proximity effect and hence the Meissner response become stronger. However, it has been reported that, at very low temperatures, the susceptibility of cylindrical structures shows a reentrant behavior and even has paramagnetic region.[4]

Recently, it has been clarified that in normal metal/superconductor junctions, if the interface is spin-active, induced superconducting pairing in the normal region can change its symmetry from even-frequency pairing to odd-

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frequency pairing[5, 6], similar to ferromagnet/superconductor junctions[7, 8]. The emergence of odd-frequency pairing is manifested as a zero energy peak in the density of states. [9, 10, 11] Here, even- or odd-frequency means that Cooper pair wavefunction is even or odd with respect to Matsubara frequency (or imaginary time).[12] If proximity induced pairing symmetry changes, the associated Meissner effect will also change qualitatively.

In this paper, we study Meissner response in the normal metal attached to superconductor where the interface is spin-active. We find that orbital magnetic susceptibility of the normal metal shows quite complex dependence on junction parameters. In particular, the magnetic susceptibility depends on the temperature in an oscillatory fashion, accompanied by its sign change. We also show that magnetic field and current density can spatially oscillate in the normal metal. These results are due to the generation of odd-frequency pairing which stems from the spin-active interface.[13]

We consider a junction consisting of a diffusive normal metal (DN) with a length L and resistance Rd, and a superconductor. The interface between the DN and the superconductor at x = L has a resistance Rb (or tunneling conductance G_T) and the surface at x = 0 is specular. A weak external magnetic field H is applied in z-direction. We consider spin-active interface at x = L which is described by the mixing conductances which reflect the spin rotation upon reflection and transmission at the interface. [14, 15] To evaluate the mixing conductances, we model magnetic barrier (interface) region as a rectangular potential V with the exchange field h in z-direction and the width d, following Ref.[15].

To study the Meissner response, we adopt the quasiclassical Green's function theory.[16] When a magnetic field is applied parallel to the interface, rich and nontrivial screening effect occurs. Within the linear response theory, the current distribution flowing in y- direction is given by [2]

$$j(x) = -8\pi e^2 N\left(E_F\right) DT \sum_{\sigma,\omega_n>0} \sin^2\theta_\sigma\left(x\right) A\left(x\right) \tag{1}$$

where A(x), N(E_F) and T denote the vector potential, the density of states at the Fermi energy and the temperature of the system, respectively. $\sin\theta_\sigma$ is the anomalous Green's functions.

By solving the Maxwell equation, we finally obtain the expression of the orbital magnetic susceptibility, [2]

$$-4\pi\chi = 1 + \frac{A(0)}{HL}$$

We set h/E_F = 0.01, Rd/Rb = 10 and 16 π e^2 N (E_F)D^2 = 1000. Below, ξ and Tc denote the superconducting coherence length and the transition temperature, respectively.

Figure 1 shows susceptibility at L/ξ= 10 with V/E_F = 0.95 as a function of the temperature T. We find that the susceptibility oscillates with temperature, and, over some region, paramagnetic state, namely that with positive χ, appears. When mixing conductance is present, odd-frequency pairing is generated in the DN region.[5, 6] This odd-frequency pairing makes it possible to oscillate magnetic field rather than suppress in the DN region[17], as explicitly shown below. Therefore, susceptibility could be positive when odd-frequency pairing correlation is dominant over even-frequency pairing in the DN.

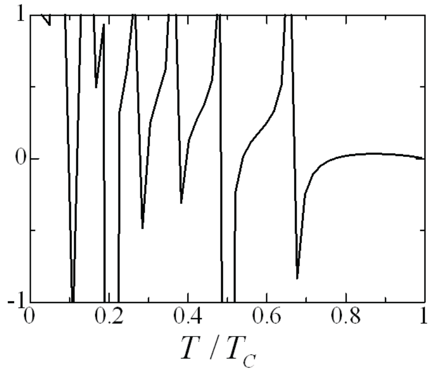

Figure 1: Susceptibility $-4\pi\chi$ as a function of the temperature.

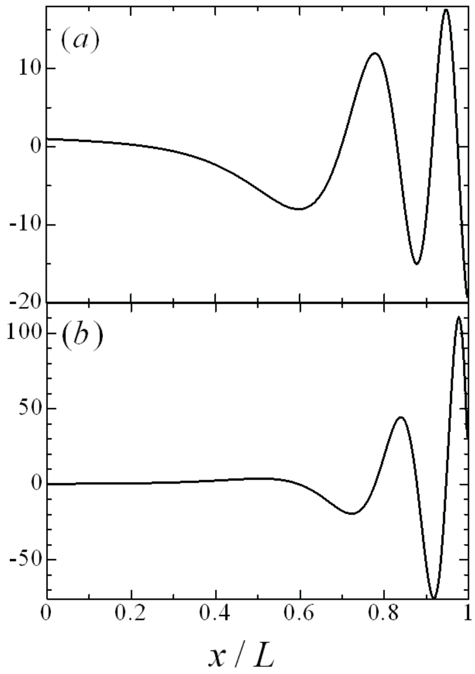

Figure 2: (a) Magnetic field and (b) current density for $T/T_C = 0.2$, $L/\xi = k_F d = 10$ and $V/E_F = 0.95$.

If purely even (odd) frequency pairing state is realized in the DN, θ becomes purely real (imaginary).[10, 17] Then, the sign of screening current Eq.(1) depends on whether induced pairing in the DN is even- or odd-frequency pairing. This drastically changes the susceptibility. To understand this qualitatively, let us consider thin limit of DN where spatial dependence of θ is negligible. Then, for purely even-frequency pairing state, the Maxwell equation reads

$$\frac{d^2}{dx^2}A(x) = k^2 A(x)$$

with a real constant k. Then, we have

$$-4\pi\chi = 1 - \frac{\tanh kL}{kL}$$

We find that it is positive definite. On the other hand, for purely odd-frequency pairing state, the Maxwell equation reads

$$\frac{d^2}{dx^2}A(x) = -\kappa^2 A(x) \tag{2}$$

with a real constant κ. The right hand side of this equation represents negative superfluid density due to odd-frequency pairing. Then, we obtain

$$-4\pi\chi = 1 - \frac{\tan \kappa L}{\kappa L}$$

We find that it can change its sign. Moreover, it can show divergent behavior near $\kappa L = \pi / 2$. In this way, we can understand the behavior of the susceptibility in Figure 1.

Figure 2 depicts (a) normalized magnetic field H(x)/H and (b) current density at T/Tc=0.2, L/ξ= $k_F d$ =10 and V/E_F = 0.95. By solving Eq.(2), we can show that the oscillation is due to the odd-frequency pairing. Therefore, Figure 2 also indicates that odd-frequency pairing does not repel magnetic field. The relation between susceptibility and magnetic field can be obtained along the same line.[13] This indicates that, to realize paramagnetic state, H(L) has to be larger than H, namely, magnetic field at the interface should be larger than that at the surface of the DN. To attain anomalous Meissner effect, dominant odd-frequency pairing in the DN is required. This can be acheived when magnitude of mixing conductance is comparable to that of tunneling conductance (G_T)[5].

We find divergent behaviors of the susceptibility, the magnetic field and the current density. However, their magnitudes would be reduced due to spin-orbit scattering or magnetic scattering in the sample [18] but the behaviors presented above are robust against this effect within the reasonable range.

In summary, we have studied Meissner response in the normal metal attached to a superconductor where the interface is spin-active. We found that the susceptibility depends on the temperature in an oscillatory fashion, accompanied by its sign change. We also showed that magnetic field and current density can spatially oscillate in the normal metal. These results are attributed to the generation of odd-frequency pairing arising from the spin-active interface.

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